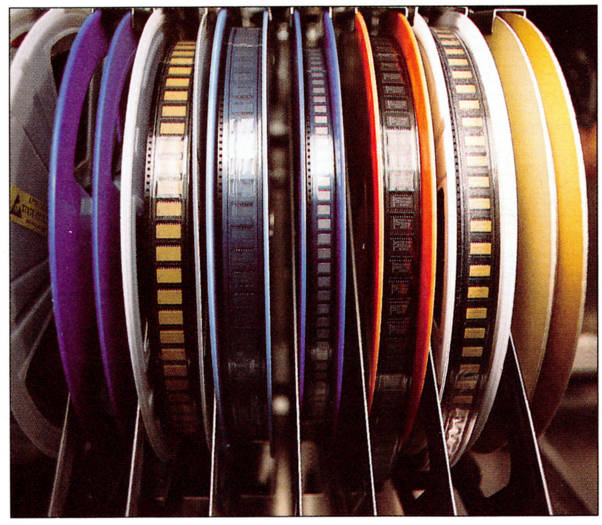
SQUARE ONE
Apple's Fremont factory produces the computers and peripherals that are responsible for 60 to 70% of Apple's revenue. This 160,000-square-foot board-assembly building is where Macintosh production starts. By the time a Mac is packaged 20 hours later, it will have travelled some 1,300 feet on conveyor belts and lifts. About 1,000 employees will have helped it on its way.

BEHIND LOCKED DOORS

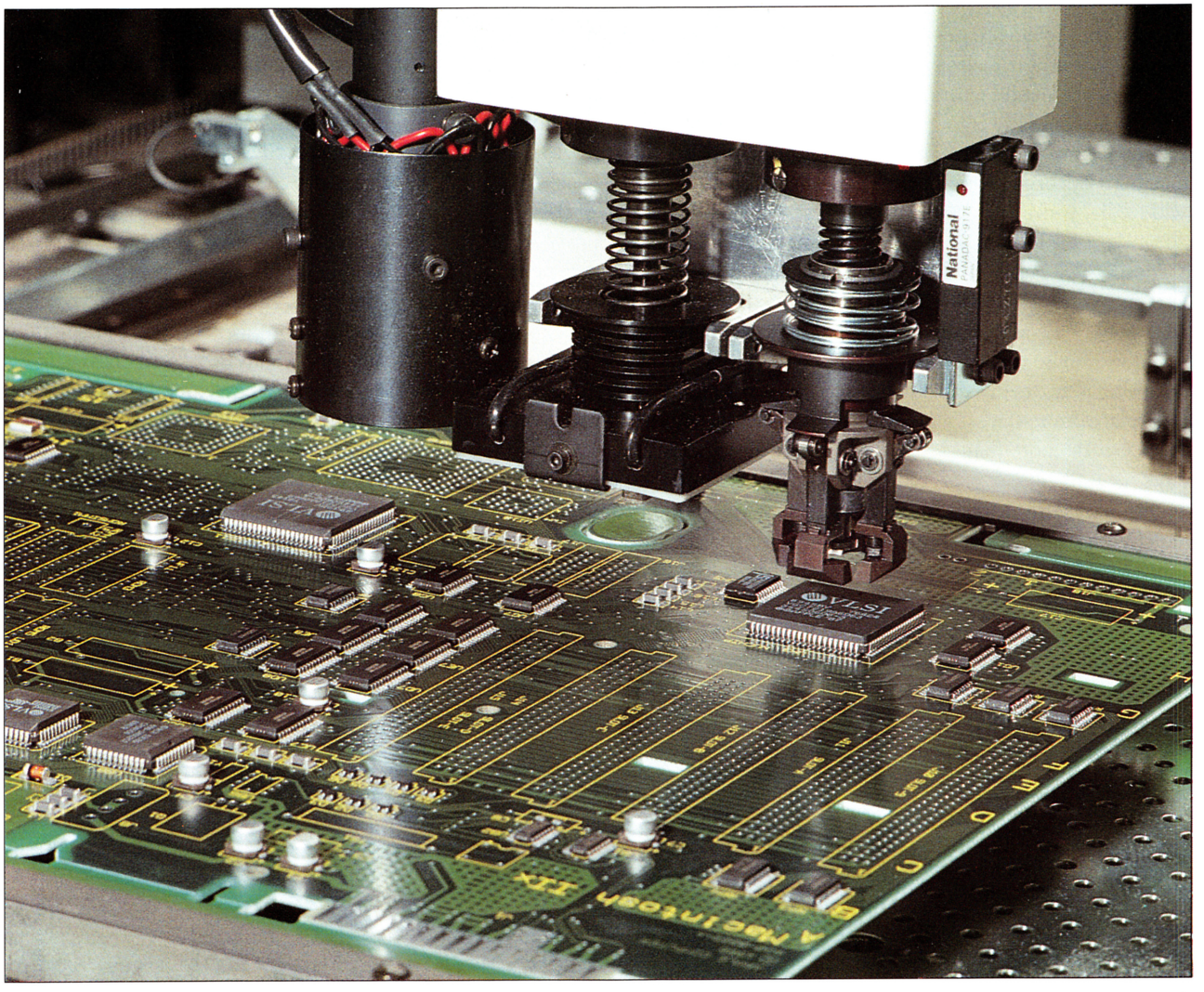
MANUFACTURING THE MAC

by Cheryl England Spencer

When the Macintosh IIcx was first introduced, Jean-Louis Gassée engaged in a brief display of showmanship. By personally assembling the computer in less than a minute he demonstrated just how easy it is to take apart and put together the IIcx. The demonstration received a lot of press, but the gist of the commentary was "Oh, a cute trick". Few people realised its significance. No other computer manufacturer – not Sun, not IBM, not even NeXT, with its shiny, automated board-assembly line that Steve Jobs likes to flaunt – has developed a machine that is as easy to assemble. What Gassée's stunt really signaled is that Apple has completely changed the way it makes computers.



THE JOURNEY BEGINS
The Mac's journey really starts here, with the chips that make up a circuit board. These chips come in strips that are wound around plastic 35mm (or larger) reels. Shown here are resistor packs (square, yellow chips), logic arrays (square, black chips), and oscillators (square, metallic chips). Once employees place these reels into automatic parts insertion machines, the factory spins into motion.



MACHINES IN MOTION
Automatic-insertion machines pick up each part, photograph it to ensure that it is not damaged, and swiftly place it in the correct spot on the circuit board. Placement of parts must be accurate to within 1/1,000 inch. Each tool can handle five differently shaped parts down to 1/16 inch in size (Apple's smallest part is 1/8 inch); the machines can be programmed to change tools within a couple of seconds. Boards are then inspected by hand and sent to a machine that adds a layer of epoxy to secure parts such as capacitors, resistors, and diodes. Oddly shaped parts (1% of all parts on a Macintosh IIcx or IIci) are then placed manually.

After two sequestered years, Apple is finally starting to crack open the doors of its manufacturing facilities. We are seeing that the pace of innovation in Apple's factories has been lightning fast during the last couple of years. Leading-edge robots that were the pride and joy of Apple's manufacturing facilities two years ago have been phased out. Assembly lines have been adapted to the newer Macintoshes and, in the six months between my last visit to the Fremont factory and the publication of this article, the Macs being assembled in each of the buildings will have been reshuffled once again, with even more automation incorporated into the process.

Many of these changes are occurring because Apple realizes just how important the manufacturing process is. If the company is to continue to expand, it must be able to introduce high-quality products on a worldwide scale, within the shortest possible amount of time. In the fiercely competitive personal computer market, Apple considers technological innovation its key advantage. But Apple cannot exercise this advantage if it cannot bring new designs quickly to the marketplace. Yesterday's innovation is little more than yesterday's news.

To keep pace with Apple's design achievements, manufacturing must accomplish four key objectives: (1) from the outset, products must be designed so that they are easy to manufacture; (2) for reliability, components must be standardised; (3) automation must be carefully implemented; (4) factories must be flexible enough to adapt to changing product configurations.

With these considerations in mind, I examined the insides of two Apple factories – Fremont's state-of-the-art plant and the Singapore plant. What follows is a behind-the-scenes peek at what Apple has been so quietly hiding behind locked factory doors.

Form and function

Only a few miles from Apple's Cupertino, California, headquarters sits the Fremont factory – five buildings that house over 47,000 square metres of manufacturing space. About half of the computers Apple produces come from here, as well as a majority of Apple's peripherals, such as monitors, printers, and scanners. Two other manufacturing facilities – one in Singapore and one in Cork, Ireland – churn out the rest of Apple's products.

The Fremont factory manufactures products for the United States and Canada and serves as a test bed for new products. The Singapore facility produces Macintosh SEs and SE/30s for the Pacific region and Macintosh Pluses and Apple IIs for both the Pacific and the United States. The factory in Ireland produces all products for 15 European countries.

One thing that all of these manufacturing facilities have in common is that their efficiency depends heavily on how well the Mac is designed – a fact that Apple factory workers have witnessed firsthand. "The Macintosh II was a nightmare," says Matt Carter, Apple's former production engineering manager. "We'd try to surface-mount components and the board would pop and break. If anything went wrong, we had to take the whole machine apart to fix it."

Similarly, the original SE proved troublesome. For instance, it has nine fasteners of several different types. On an assembly line, workers must place each screw, pull down the appropriate electric screwdriver from where it hangs above them, and then drive in the screw. To further complicate matters, workers must flip the Macintosh SE's chassis as it moves to various assembly stations. Viewed from above, the assembly line is a buzz of organised and rhythmic (but wasted) motion. Had this inefficiency continued, Apple would not have been able to introduce four new Macs last year, nor would its factories have come close to meeting demand for the new products. (Industry experts agree that Apple's troubles in meeting initial demand for the Macintosh Portable were due to a shortage of the active matrix display.)

Recognising that streamlining production would be essential to maintaining market share, Apple reorganised so that engineering, manufacturing, and product marketing were all in the same group.

HOMEGROWN MACHINERY
Several of the machines Apple uses are designed to perform one specific, repeatable task. This machine, which was designed and built in Fremont, rivets connectors to a board so that they stay tight while the board takes a rough ride through the wave-solder machine.

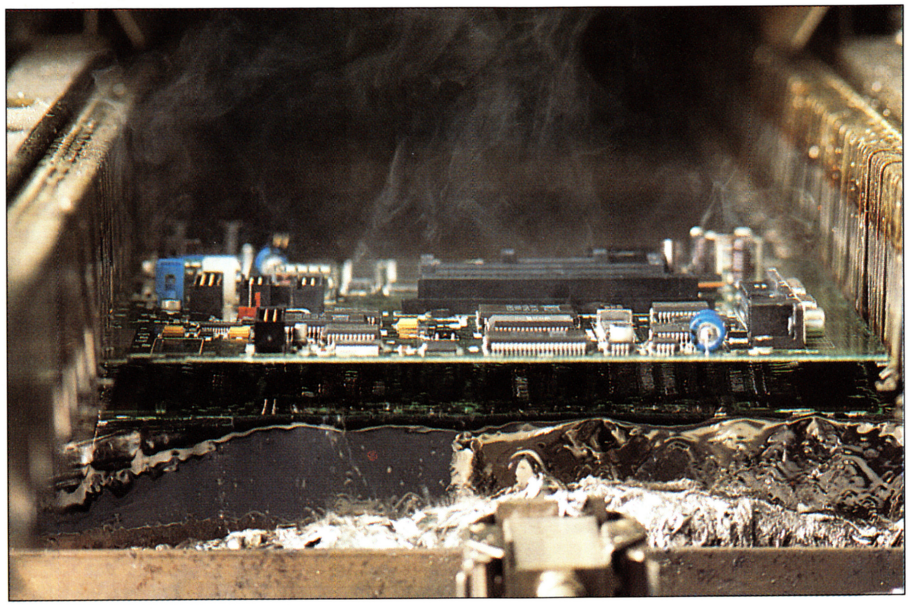
The tighter focus and greater cooperation between departments worked. The Macintosh SE/30 and Macintosh IIx contain 80% surface-mount components and 20% through-hole components – a complete reversal from earlier Macs that contain only 20% surface-mount components. Surface-mount components are placed on the top surface of the board, while through-hole components contain pins that fit into holes on the board. Surface-mount components require less board space and less power, and work at higher speeds than through-hole components; they are also easier for machines to place correctly. But it is on the newest Macs, those engineered from scratch, that Apple's design awareness really pays off.

Just take a look back at the assembly lines. The Macintosh IIcx and IIci line seems almost languid in comparison to the Macintosh SE line. All of the parts snap in easily. The whir of the screwdrivers is almost absent. From a distance, the visitor is under the illusion that the pace of production is much slower here.

This perception is misleading. The Macintosh IIcx is 38% faster to manufacture than the Macintosh SE, even though the machines have a similar number of components (not counting the Macintosh SE's monitor). The faster assembly is due to the Macintosh IIcx's snap-in parts, surface-mounted chips, and Apple's ability to integrate more functionality into fewer chips. The fact that the Macintosh IIcx, the more capable (albeit more expensive) machine, requires so much less time to make

THE SOLDER PASTE RIVER

On the outside, a wave-solder machine looks like a large freezer box with a plastic top. But by peering inside, you can see the steamy river of solder paste. Heated to a torrid 237 degrees Centigrade, the paste secures hand-placed parts and through-hole components to the board. The width of the solder paste river can be adjusted to either 8 inches or 12 inches to correspond with the size of the board. Boards then pass through another machine that degreases them. They are hand-inspected again and the edges that were left on—so that they could be handled by machines and people—are trimmed off. Apple's factories are very well ventilated; no chemical smells are noticeable.



FLEXIBLE MANUFACTURING
Completed boards make a trip to either the flexible manufacturing facility, where high-end Macintoshes are assembled, or to the building where compact Macs are assembled. The flexible manufacturing facility is designed to produce several styles of Mac. Because many of the high-end Mac's parts snap in, workstations in this factory do not need to hold a variety of tools, making a transition between product lines easier. On the morning this photo was taken, Macintosh Portables were being assembled. Workers in the foreground are putting finishing touches on the computers – snapping in keyboards, downloading system software and HyperCard (a 75-second procedure), and cleaning off the screen.

than the Macintosh SE illustrates the benefits of Apple's manufacturing advances. Recently, however, a slight pall was cast over some of the advances. Apple reorganised once again – this time putting engineering in a group separate from manufacturing and marketing. It remains to be seen whether top Apple executives learned their lesson with the manufacturing mishaps of the Macintosh SE and II, and whether the separate manufacturing and engineering groups will cooperate effectively.

Parts is parts

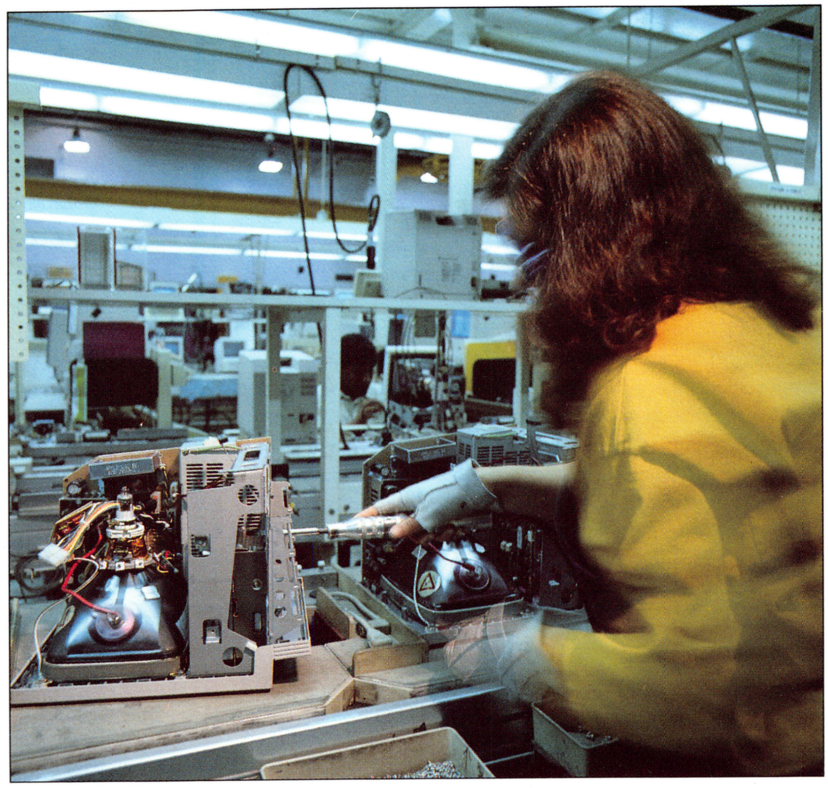
Not only must Apple worry about

DELIVERING SUPPLIES
In the flexible manufacturing facility in Fremont, parts are distributed via conveyor belts. In the Singapore factory, however, five automatically guided vehicles deliver bulky materials. A Macintosh tracks inventory at each assembly station and notifies vehicles by radio when supplies are running low. The vehicles (which are programmed to play "Home on the Range" when moving) pick up and deliver incoming supplies. How do the vehicles know where to go? They count the number of dark and light floor tiles they pass over. Even more remarkably, the rubber–bumpered vehicles can sense objects in their paths, thus ensuring that no workers are hit.

the number of components a Mac has and how easy they are to insert, the company must also make sure the components are top quality. When Apple first began producing Macs, components often did not come in consistent sizes. "In the early days," says Michael Mikel, a robotics expert and onetime Apple engineer, "a big problem was standardisation of components. We'd have to make changes to the Mac, things like enlarging the holes in the board, to allow for variations." But as tolerances become tighter on boards, Apple can no longer fudge specifications that way – it must have more control over the sizes of parts.

Although the specifications remain standard worldwide, each Apple factory buys its components from local suppliers. For Apple Computer Singapore, quality components are not an issue. At the Fremont factory,

(continues)



ASSEMBLING A MACINTOSH SE
Unlike the newer Macs assembled in the flexible manufacturing facility, compact Macs have many parts that must be screwed together. For instance, the Macintosh SE chassis requires five screws and the case requires four; the Macintosh Portable does not contain any screws. To put all those screws into a Macintosh SE, workers must flip the chassis several times. Once this worker finishes driving the final screws into the chassis, she presses a button to send the computer down the line to other workers who add hard drives and EMI shielding.

however, relationships with suppliers must be constantly monitored.

While most overseas consumer-manufacturer relationships are congenial, US parts suppliers and manufacturers have traditionally fought each other. Parts suppliers do not want to invest additional time and money to meet manufacturers' special specifications; the manufacturers do not want to fully reveal their future plans. And both sides are pushed by investors to improve their short-term profits. "Auto-insertion machines made in the US come with on-the-fly parts verification," says Matt Carter, the engineer who ran all operations in the original Fremont factory. "The Japanese machines don't. So when we were purchasing some equipment from a Japanese vendor we requested a verification facility. Their response was, 'Why? Don't you get good parts from your suppliers?' "

Apple devotes a lot of energy to overcoming the traditional supplier-manufacturer antagonism. Over the years, the company has developed better-than-usual relationships with its vendors, partially because suppliers who accommodate Apple's requests receive a larger share of the company's business. Apple also spells out its quality requirements in supplier contracts and uses a supplier certification program so that some suppliers can ship parts directly to stock, bypassing the time-consuming test process.

Still, Fremont tests many more components than does Apple Computer Singapore, which tests fewer than 30% of its components. As long as the lack of cooperation between manufacturers and suppliers continues, Apple will have an uphill battle in Fremont.

Grappling with robots

Ever since automation first appeared, social commentators have painted a vision of a useless work force displaced by the very machines that they created. Apple has a history of automating as much of the logic-board assembly as possible – not because the company is trying to eliminate workers, but because automation increases the Mac's reliability. Chips are becoming smaller – the smaller they get, the harder they are to place accurately and quickly by hand. Also, it becomes easier

(continues)

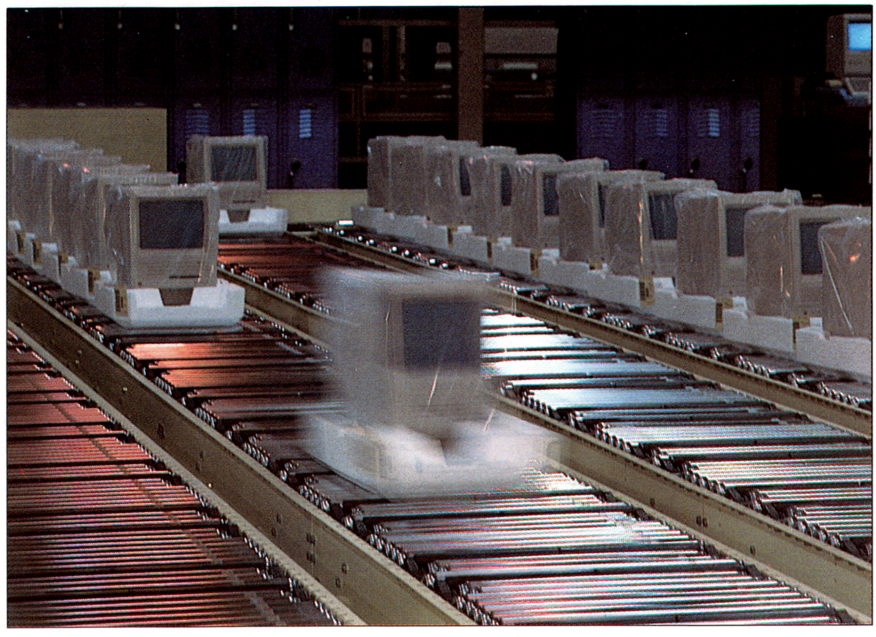
requires retooling and fixtures, it can take from one hour to half a day." Fremont has become fast enough and flexible enough that it can make custom configurations for major customers without hampering its ability to meet normal product demand.

Once a Mac is configured, a scanner reads a bar code that has been attached to the Mac since step one and sends it down the proper conveyor lane – Macintosh SE/30s with a 40Mb hard disk go into one lane, Macintosh SE/30s with an 80Mb hard disk go into another. When enough Macs of a given configuration are made to fill an order, those Macs are forwarded to a giant machine that automatically boxes them and spins shrink-wrap over the whole package. These boxes are loaded directly into a truck, ready for delivery.

This type of tracking and sorting process has to be exact, especially in the Cork factory, which must not only produce the standard Mac configurations but also produce each configuration in 17 languages. "Two years ago Apple shipped 350 configurations worldwide," says Fred Forsyth, vice-president of worldwide manufacturing at Apple. "This year [1989] Apple shipped 1,200 configurations, and most of those are out of Cork."

Personal attention

After spending several days in Apple's factories, watching Macs grow from bare boards to shrink-wrapped boxes, what remains most vivid is not the robots or the intricately designed system, for these will change yet again by the time I come back. Instead, it's the image of the people who make the factory work. Employees hand-inspect each board under a magnifying glass as it comes off the assembly line, they adjust monitors by hand, and they wipe off the Mac's plastic case before it is packed.



ACCUMULATING MACS
As the Macs move down the line, a worker settles each one into its Styrofoam bottom and sends it on its way. The Macintosh in the background is running a custom HyperCard application that reads a bar-code label on the front of each finished Mac. Macs are sorted and sent down a specific lane of this accumulator. When a quota of, say, Macintosh SEs with hard disks is reached, a worker prompts the controlling Macintosh to send the finished computers to other workers who add the rest of the Styrofoam packaging, the manuals, and the cables. A giant machine boxes each Mac and spins shrink-wrap over the whole package. Macs are loaded directly into the trucks (or onto ships, in Singapore) that will take them from the factory.

In spite of the criticism Apple deservedly used to receive in the US for its short warranty, the company still cares about its products. That care is reflected in the way Apple treats the people who so directly affect the quality of the Mac. One of Apple's most successful experiments occurred during production of the Macintosh IIcx. A specially trained group of people nicknamed Team Avanti took responsibility for planning production schedules, worked with purchasing to solve supply problems, and gave their input on how easy the new design was to assemble.

Even outside Team Avanti, Apple is training its workers to interact directly with people other than their direct supervisors, frequently cutting through layers of management overhead. "Typically, if there is a problem with a part, the operator gets the industrial engineer who then goes to purchasing. Purchasing then goes to the vendor," says Campi. "In some cases now the operator goes directly to the vendor."

Apple long ago discovered that caring people are the driving force behind any innovation or advancement. The company's manufacturing arm continues to embody that core principle while, at the same time, moving ahead to implement clean product design, quality parts, automation, and manufacturing flexibility. It is the degree to which Apple is able to coordinate these concerns that will determine the company's impact during the coming decade.

MAC

TESTING A MONITOR
Now that everything but the outer case has been assembled, a worker adjusts the monitor's focus, brightness, and voltage levels, as well as the image area's height and width. The monitor is then glued down and the adjustments are rechecked. If the monitor fails to meet Apple's specifications, it is sent to a rework area to be fixed. A worker places the outer casing on Macs that pass the monitor test, and a machine presses the casing securely into place. A few screws are inserted and the Mac is ready for final testing.

and flashes until an operator comes to the machine's rescue.

If the idea that automation will eliminate the need for workers is a myth, the idea that robots will lead to a lights-out factory – where machines work unattended in a dark room, stamping out identical products day after day – is an even bigger myth. In Japan, where such factories exist to produce high-volume, low-cost items such as televisions and VCRs, many of the robots are simply machines that use actuators to do one thing reliably.

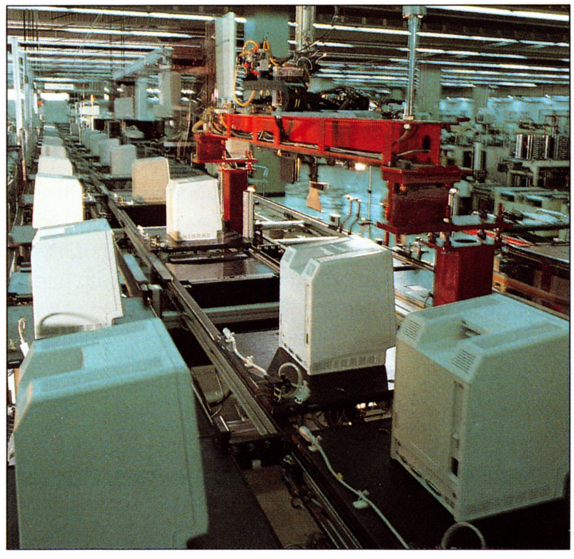
Although Apple designs some of these simple types of machines for use in its factories, many of Apple's robots are much more complex – and much more flexible. These machines consist of an arm mounted on a table. At the end of the arm is a gripping device, which can adapt to small changes in the size and shape of components. Operators can program robots to change tools so that instead of needing a different robot for each component – one for cams, one for VLSI chips, for example – the same robot can place a variety of parts on a board before sending it on to the next step.

Even better, operators can reprogram the robots to assemble new boards or to switch from one type of board to another as consumer demand changes. For instance, because all Apple boards come in one of two widths – 8 inches or 12 inches – all products requiring the same size board can be manufactured on the same line. At Fremont, for example, where there are 12 assembly lines that can produce Macintosh logic boards, the number that are producing Macs versus the number that are producing other products (such as LaserWriter boards) varies from day to day, and even from shift to shift.

Lining up for change

Although flexibility is important at the board level, it becomes critical during the final product assembly. Not only must each assembly line be able to produce different products, but it must also be able to produce different configurations of those products quickly. On any given day, for instance, Apple may need to produce Macintosh Portables, Macintosh IIcx models with only a single floppy drive, and Macintosh IIcx's with a hard disk and a floppy drive.

Changing the assembly lines to accommodate different machines or different configurations can take anywhere from a few minutes to a few hours. "Changing from Macs with 40Mb hard disks to Macs with 80Mb hard disks is almost a real-time event," says Mike Campi, director of Fremont manufacturing. "Other changes can be done between shifts. If a change



THE HIGHWAY
Apple relies heavily on conveyor belts to move supplies, boards, and Macs in all of its factories. Here fully housed Macs take a trip down Singapore's "highway" on their way to the burn-in towers (tall, metal shelves). Once there, Macs undergo at least 17 hours of tests designed to test, or burn in, all of a Mac's major components. Macs that pass are forwarded, again by conveyor belt, to a finishing area where workers test the display once again, to make sure that nothing changed during the burn-in process, and add final touches such as hand-cleaning the case. Then it's off to the packing area.